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Digital Object Identifier (DOI):
10.1088/1742-6596/922/1/012006

Published In:
Journal of Physics: Conference Series

Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

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To cite this article: Rodica-Cristina Voicu *et al* 2017 *J. Phys.: Conf. Ser.* **922** 012006

IOP Conf. Series: Journal of Physics: Conf. Series **922** (2017) 012006 doi:10.1088/1742-6596/922/1/012006

Nonlinear numerical analysis and experimental testing for an electrothermal SU-8 microgripper with reduced out-of-plane displacement

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Abstract. This paper reports the results of numerical nonlinear electro-thermo-mechanical analysis and experimental testing of a polymeric microgripper designed using electrothermal actuators. The simulation work was carried out using a finite element method (FEM) and a commercial software (Coventorware 2014). The biocompatible SU-8 polymer was used as structural material for the fabrication of the microgripper. The metallic micro-heater was encapsulated in the polymeric actuation structures of the microgripper to reduce the undesirable out-of-plane displacement of the microgripper tips, and to electrically isolate the micro-heater, and to reduce the mechanical stress as well as to improve the thermal efficiency. The electro-thermo-mechanical analysis of the actuator considers the nonlinear temperature-dependent properties of the SU-8 polymer and the gold thin film layers used for the micro-heater fabrication. An optical characterisation of the microgripper based on an image tracking approach shows the thermal response and the good repeatability. The average deflection is ~11 µm for an actuation current of ~17 mA. The experimentally obtained tip deflection and the heater temperature at different currents are both shown to be in good agreement with the nonlinear electro-thermo-mechanical simulation results. Finally, we demonstrate the capability of the microgripper by capture and manipulation of cotton fibres.

1. Introduction

Micromanipulators developed as micro-robotic arms or as microgrippers are important tools for handling, manipulating, picking and placing delicate micro-objects. The applications of such devices include biological micro-manipulation (living cells, blood vessels, and tissues), and micro-assembly of Micro-electro-mechanical Systems MEMS/MOEMS components (micro-gears, micro-mirrors, lenses, fibers) and micro-robotics applications.

Usually, such microgrippers are often integrated with actuators that are used for energy conversion, motion generation and force production [1-3]. Different actuation techniques can be integrated with MEMS in order to obtain the desired performance, such as electrostatic, piezoelectric, thermal, shape memory, pneumatic or magnetic strategies. The advantage of the thermal actuators mainly depends on the coefficient of thermal expansion (CTE) of the structural material. Frequently, the structural material of the actuators is silicon, polysilicon or aluminum. But, for example, due to the small CTE, silicon

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produces small mechanical deflection. The alternative materials used for the structural part of the actuator are polymers which are preferred for thermal actuation due to the low Young modulus and high CTE [4-5].

Different microgrippers have been considered using the SU-8 polymer based thermal actuators designed on different configurations such as, U-shape or V-shape based designs. This is proving interest in the bio-micro-manipulation domain [2-14]. SU-8 is a highly cross-linked epoxy-photo-polymer which has been the preferred polymer material for fabrication of biocompatible devices. The SU-8 polymer has a relatively large coefficient of thermal expansion (CTE) of 52 ppm/ºC [15], good mechanical strength with a Young's modulus of between 2-5 GPa [15] and a good thermal stability with a glass transition temperature of 210°C [15] which make it a proper material for manufacture of thermal actuators.

The thermo-mechanical properties of the polymers, such as SU-8, and the electrical conductivity of the metals used for micro-heaters are essential for the behavior of the thermal actuators. Previous research has studied the nonlinear mechanical and thermal properties of fully cross-linked SU-8 in order to be used for modeling of thermal actuators. The effect of the temperature on the Young's modulus, Poisson ratio and CTE was reported in different studies [4-5].

In this work, we present the results of numerical nonlinear electro-thermo-mechanical analysis and testing of an SU-8 polymeric microgripper designed using the electrothermal actuators. The SU-8 microgripper can be utilized for bio-manipulation, assembly and micro-robotic applications. In order to confirm the performance of the microgripper, the actuator was investigated by numerical simulation based on a finite element method (FEM) and the Coventorware (2014). The biocompatible SU-8 polymer was used in the fabrication process as the structural material. The gold metallic micro-heater was encapsulated in the polymeric actuation structures of the microgripper to reduce the undesirable out-of-plane displacement of the microgripper tips, to electrically isolate the micro-heater, to reduce the mechanical stress and to improve the thermal efficiency. The electro-thermo-mechanical analysis of the actuator included the nonlinear temperature-dependent properties of the SU-8 polymer and also of the gold thin metal layer used for the micro-heater fabrication. The characterization of the gripper displacement was based on an image tracking approach. The experimentally obtained tip deflection and the heater temperature at different currents are both shown to be in good agreement with the nonlinear electro-thermo-mechanical simulation results. Finally, we demonstrate the capability of the microgripper by manipulation of cotton micro-fibers.

2. Design and Fabrication

The design and the fabrication of the polymer microgripper using a sandwich structure with the metallic micro-heater embedded in the polymeric actuation structures of the microgripper (figures 1 and 2) were reported before [11-14]. The fabrication is based on the structure release using the designed chips with different microgripper structures (figure 3).

2.1 Design

The polymer microgripper was designed using the thermal actuators in normally close operation. The initial opening of the microgripper is of 10 μm (figure 2). When the gripper is electro-thermally actuated, the tips will open and can grip a micro-object. The total length of the gripper is 1300 μm. The arms were designed with a width of 20 μm. A metallic micro-heater is embedded between two SU-8 layers with the same thickness of around 10 μm. The track width of the heater was designed to be 10 μm and the thicknesses of the heater layers were 10/300/10 nm for Cr/Au/Cr films.

The microgripper was designed symmetrically with embedded metallic micro-heaters in the structural material of the grippers (figure 1), the SU-8 polymer, in order to reduce the undesirable out-of-plane displacement of the gripper, to obtain the electrical isolation of the heaters and to reduce the mechanical stress that can occur in the structure [12-14].

The substrate where the structure will be fixed after fabrication can be either a silicon or a glass wafer.

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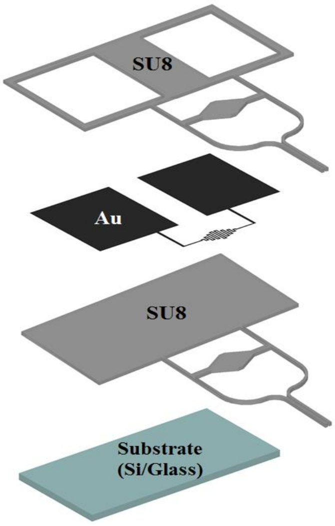


Figure 1. Exploded view of the 3D microgripper model with embedded heater between two SU-8 layers.

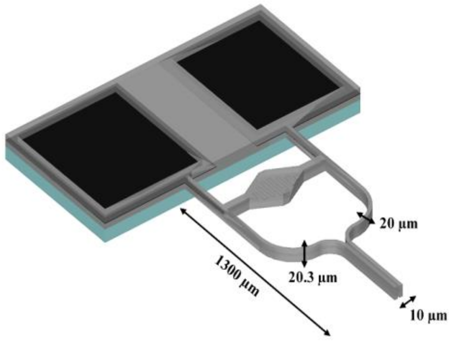
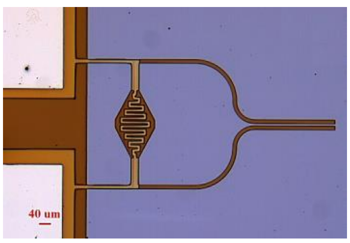


Figure 2. 3D model of the microgripper used in FEM simulations (Coventorware).

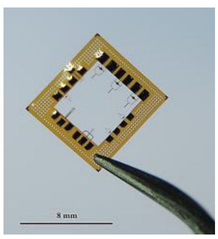
2.2 Fabrication

The optimized gripper design planned for manufacture consists of a symmetrical structure of three material layers with the metallic layer for the heater embedded between two SU-8 based structure layers having the same thickness, as described previously [13-14].

The fabrication of the microgripper is based on a 3-mask process. The two masks used for the SU-8 structural gripper configuration have similar designs, one of the masks having openings for producing access windows on the metallic pads. The third mask was used for the micro-heater configuration. The heater and pads were obtained using a lift-off process using an AZ photoresist consisting of metal films of Cr/Au/Cr. The OmniCoat stripper (MicroChem) was used in order to completely release the final structures. The details of the fabrication work have been reported also previously in [13]. Figure 3 shows that the fabricated microgripper before release and the released chip with different SU-8 microgrippers are well configured.



a)



b)

Figure 3. Optical microscope pictures: a) a fabricated SU-8 microgripper before release; b) one chip with released SU-8 microgrippers;

3. Numerical Simulation and Experimental Testing

Numerical analysis, characterisation and experimental testing were performed in order to determine the microgripper behaviour in air. Each microgripper was mounted on a hexapod based robotic system. A microscope based optical vision system and an image tracking software was used to realise the measurements regarding the displacement of the gripper tips. Further, the measured TCR was used to determine the heater temperature in gripper operation [13-14].

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3.1 First Electro-thermo-mechanical Analysis

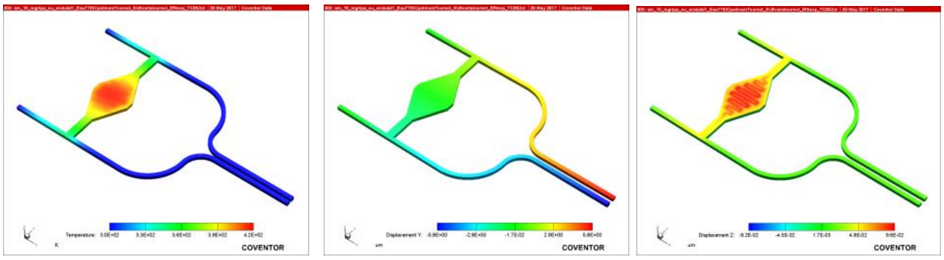
Coupled electro-thermo-mechanical FEM simulations were completed using the MemMech simulator (Coventorware). A simplified 3D microgripper model (figure 2) was meshed using hexahedral parabolic elements (Extruded bricks). The number of volume elements was optimized by choosing the proper size and using the Split and Merge algorithm. The surface boundary conditions were set for the simulations. The initial temperature of the whole structure and the temperature of the environment were considered to be T_0=27 ºC, with respect to the Coventorware settings for this type of analysis. The effect of radiation was neglected since the polymeric structure works at low operating temperatures.

For the first simulation analysis, constant values for the material properties of SU-8 were used. The Young's modulus of the SU-8 was set at 4.6 GPa. The CTE was fixed at 52 ppm/ºC and the thermal conductivity at $2x10^5$ pW/µmK. For the gold layer, we used a Young's modulus of 77 GPa reported for thin films. For the thin Cr/Au/Cr films, a measured temperature coefficient of resistance (TCR) of 0.00147/°C was used [13-14] in order to take into account temperature effects on electrical properties. The electrical conductivity of the gold layer, σ was set using equation (1):

$$\sigma(T) = 1/\{\rho_0\,[1 + \varepsilon \cdot (T - T_0)]\} \tag{1}$$

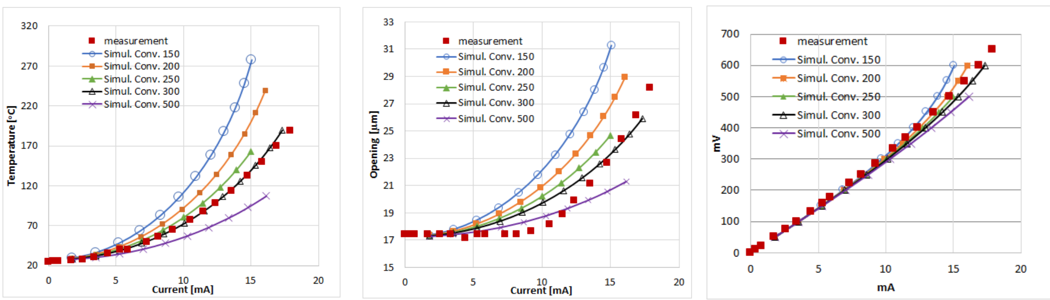
where ρ_0 is the resistivity at T_0, ε is the TCR of the Cr/Au/Cr layer. The air convection coefficient was variated between 150 [1] and 500 W/m^{2}K in order to obtain the best fit with the experimental results.

The distribution of the temperature and mechanical behavior of the microgripper at 15mA actuation current can be observed in figure 4. The temperature remain around 27 ºC at the tips and the out-of-plane displacement under 0.1 µm. The simulated values of the temperatures reached in the arms are presented in figure 5 a) and the simulated in-plane deflections of the tips as function of electrical current in figure 5 b) when the convection coefficient was varied. When the convection coefficient is near 300 W/m^{2}K the results of simulation and measurements are in good agreement regarding the temperatures (figure 5 a)) and electrical currents (figure 5 c)). The results for displacements are not in such good agreement (figure 5 b)).



a) b) c)

Figure 4. FEM coupled electro-thermo-mechanical simulation results at 15 mA: a) Temperature distribution in the microgripper; b) In-plane deflection; c) Out-of-plane deflection (Coventorware).



a) b) c)

Figure 5. Simulation results vs measurements: a) Temperature values as electrical current; b) Tips opening vs electrical current; c) Electrical Current vs potential.

3.2 Second Electro-thermo-mechanical Simulations

In order to improve the agreement between the simulation results regarding the displacements and the measurements results, the mechanical and the thermal material properties of the SU-8 were varied as a function of temperature. The dependence of Young's modulus on temperature was modelled (2) using

$$E(T) = E_0 \exp(-T/T_C) \quad (2)$$

where, the constant E_0 is 5.76 GPa and the constant temperature T_C is 55.82 °C [4-5]. Similarly, the Poisson's ratio with temperature was modelled (3) as

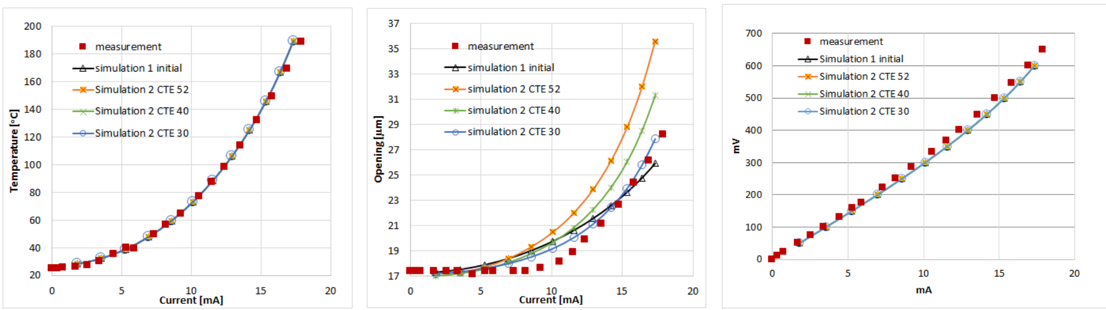
$$\nu(T) = \nu_0 + \nu_1 T + \nu_2 T^2 \quad (3)$$

where, the constants, ν_0, ν_1 and ν_2 are obtained from the experimental results [5]. The small nonlinearity in CTE for the SU-8 as function of temperature was modelled (4) as

$$CTE(T) = CTE(T_0)[1 + \varepsilon_{CTE} \cdot (T - T_0)] \quad (4)$$

where, the constant $CTE(T_0)$ is the CTE at ambient temperature and $\varepsilon_{CTE} = 0.00175\ ^0C^{-1}$ [4].

All simulations were performed for a convection coefficient of 300 W/m^{2}K. The CTE value was varied from 52 to 30 ppm/°C for SU-8. The best agreement was obtained for a CTE of 30 ppm/°C (figure 6). The out-of-plane displacement remains under 0.1 μm in each actuation stage. Further investigations can be completed varying the SU-8 material properties, such as Young's modulus, Poisson ratio and the CTE which strongly influence the mechanical behavior of the gripper (figure 6 b)).

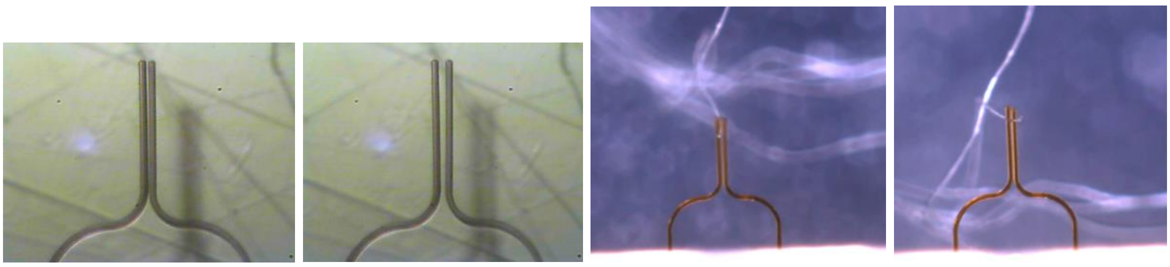


a) b) c)

Figure 6. Simulation results vs measurements: a) temperatures as function of actuation current; b) opening of the microgripper tips vs current; c) current vs potential.

3.3 Experimental Testing

The experimental testing was performed in air to analyze the openings of the microgripper when it is actuated (figure 7 a) and b)). In order to demonstrate the microgripper performance, different tests were performed by manipulating cotton fibers in air using the microgripper mounted on a robotic system (figure 7 c) and d)).



a) b) c) d)

Figure 7. Optical images of the actuated microgripper and the tips in the close and open stage: a) initial opening of around 10 μm; b) opening tips at 15 mA; c) and d) Optical images of the microgripper capturing a cotton fibre.

4. Conclusions

Electro-thermo-mechanical analysis and experimental testing of a polymeric microgripper based on electrothermal actuation have been presented. The simulations of the actuator including nonlinear temperature-dependent properties of the SU-8 polymer and the gold thin metal layer used for the micro-heater fabrication demonstrates a good agreement between the results of experiments and numerical analysis. The average in-plane displacement is ~11 µm for an actuation current of ~17 mA. The out-of-plane displacements remain under 100 nm. We demonstrate the gripping capability of the microgripper by capture and manipulation of cotton fibers.

Acknowledgments

This work was supported by a grant of the Romanian National Authority for Scientific Research and Innovation, CCCDI – UEFISCDI, project number 22/2016, within PNCDI III, ERA-MANUNET-II-Robogrip project "Microgrippers as end-effectors with integrated sensors for microrobotic applications (ROBOGRIP)" (2016-2017).

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